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JOINT SERVICES ELECTRONICS PROGRAM

Thirteenth Annual Report

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The Ohio State University

·ElectroScience Laboratory·

Department of Electrical Engineering
Columbus, Ohio   43212

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In Memoriam
Professor J.H. Richmond
1922 – 1990

Prof. J.H. Richmond died suddenly on November 30, 1990 of a heart attack. This was only two days after he completed the section in this report on the interaction of electromagnetic microwaves with nonlinear devices and nonlinear media. Professor Richmond has been a member of the staff at the ElectroScience Laboratory since 1952. He completed his Ph.D. degree in 1955 and retired as a Professor from the Electrical Engineering Department of Ohio State University in 1985. Prof. Richmond was a Life Fellow in the IEEE and was the recipient of one of 18 Centennial awards from the Antenna and Propagation Society. He nevertheless continued his research activities at the ElectroScience Laboratory and actually increased his own research activities during the last few years of his life.

Professor Richmond's research in the now commonly accepted moment method represented a worldwide guiding light to users and researchers alike in this important technology. He represented an important asset to the ElectroScience Laboratory in many ways. As a consultant for proposed theoretical concepts, there was a steady parade into his office of senior staff, graduate students, and visitors to discuss their specific problems. The use of his computer codes was an initial step for many graduate students. He was contacted by many external researchers who wanted to discuss some phase of his work. He will be sorely missed.

Professor Richmond's published papers were concentrated in the Antenna and Propagation Society of the Institute of Electrical and Electronic Engineers and Radio Science. In his later years, he did not participate in the various electromagnetic symposia, so many readers would not recognize him, but all of those involved in his technical areas would be aware of his published research.

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I. DIRECTORS OVERVIEW

This report represents the thirteenth annual summary of The Ohio State University Joint Services Electronics Program (JSEP).

There have been a total 27 Ph.D. and 20 M.Sc degrees in Electrical Engineering obtained under partial JSEP sponsorship. There are currently 9 Ph.D. and 1 M.Sc. student being partially supported under JSEP.

As may be seen in the Annual report Appendix, 14 reprints have been included in the period September 1989 to September 1990. In addition, 13 papers have already been accepted for publication in the coming year, an additional 12 papers have been submitted, and an additional 12 papers are in preparation.

II. DESCRIPTION OF SPECIAL ACCOMPLISHMENTS AND TECHNOLOGY TRANSITION

The transfer of the compact range and target identification technology initiated under JSEP support for time domain studies continues to make large advances. Using other sources of support, design for a mini chamber has now been generated and has been constructed. This range is designed to study smaller targets at higher frequencies.

The research has proven to be of intense interest to DoD and the Aerospace industry and our Compact Range Consortium represents a major cross section of the Aerospace and Electronic Industries, including additional major support from several DoD agencies. In fact, the total support in these experimental studies substantially exceeds our JSEP support. This research is truly guiding a major portion of this technology in the USA and has been extremely important for stealth technology advances. However,

these advances were only possible because of the initial JSEP support. This continues to be a case where a small investment of basic research funds have been leveraged to generate much larger support and have achieved major contributions for DoD. This has also lead to OSU-ESL involvement in committees discussing Ultra Wide Band radar systems.

Our target identification work, also partially funded at one time under JSEP Time Domain Studies, is also being funded by several other agencies including ONR and continues to be rather vigorous. Again, JSEP funds have been leveraged to initiate larger programs which have been supported continuously since JSEP funding was terminated.

Our JSEP research continues to focus on Electromagnetic related topics. There are three major electromagnetics areas that were pursued in the past year and a closely related study in Adaptive Arrays.

The goal of our Diffraction Studies is to not only treat new diffracting mechanisms but also to reduce their complexity so that they can be more readily applied to DoD problems. These mechanisms become exceedingly important as stealth technology advances, i.e., as scattered fields are reduced ever lower. It is the intent to reduce these analyses to the Diffraction Coefficient format so that the solution of scattered/radiated fields for aerospace vehicles will involve the use of these coefficients and differential geometry. Such solutions will then be packaged in a variety of computer codes on other projects as part of a technology transfer mechanism.

This activity has included the generation and use of simplified boundary conditions which are designated as Generalized Impedance Boundary Conditions (GIBC) and Generalized Resistive Boundary Conditions (GRBC). Dr. Rojas received the best paper award for all IEEE publications for authors under 35 years of age for his effort in this area. This later case is

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proving valuable in the design of tapered resistive cards for reducing scattered fields from edges. We are also examining the effect of terminations for open-ended waveguides and this research has resulted in a Ph.D. dissertation. Our search for an adequate corner diffraction coefficient has been rewarding in that an improved uniform corner diffraction coefficient has been generated and is discussed in yet another dissertation.

In the past, our Integral Equation Studies have focussed attention on the analysis of penetrable materials used in conjunction with conducting surfaces. These have included various tactics to reduce the computation time required, such as making use of special Green's functions so that the only unknowns are currents in the materials. Many of the basic techniques developed under JSEP support were later incorporated into user-oriented computer codes. These codes, such as the "Electromagnetic Surface Patch Ccde (FSP)" are now widely used in government and industry. Our current research in this area involves much more general media and we have been successful in treating chiral and non-linear media via the integral equations approach. The research in the chiral media scattering has resulted in several papers and a dissertation is nearing completion. Another dissertation by a math student is being completed on the subject of artificial media.

The Hybrid Approach represents novel analyses involving more than one basic technique such as was done originally at the ESL by combining diffraction and integral equations which was one of the earlier such solutions. One of our initial efforts involved the scattering from structures that resembled jet intakes and exhausts. Several decades ago, these were supposedly geometries whose scattering properties would never be treated analytically with any degree of success. Our recent work has been overcoming most of these difficulties as will be seen in the deep cavities discussed in

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the appropriate section. Both government and industry are becoming the primary supporters for this effort and again JSEP support has been used in the initial stages of study that have been carried to the extent that others are now providing the major funding. Research on more shallow antenna cavities has continued under JSEP support and we expect that this effort will also be of general interest to many. We are considering these same techniques to evaluate the electromagnetics environment on naval ships. This represents an important topic for future research and should have a substantial impact for the Navy.

Another topic of interest here is the electromagnetic properties of stripline systems. To treat such devices rigorously requires the inclusion of a very complex Sommerfeld integral. Asymptotic forms of this integral have been obtained that greatly simplify such analyses. The form of the solution remains uniformly valid even for lateral field and source point separation as small as a third of a wavelength and has been extended to include double layers. This and future efforts should contribute substantially to the design of MMIC structures.

These asymptotic forms coupled to a judicious choice of basis functions for appropriate choice of boundary conditions for the geometry (coupler, bend, transformer, etc.) not only simplify the analysis, but contribute substantially to understanding the physical mechanisms involved. The Hybrid approach is being used to generate solutions for structures where neither moment method or asymptotics can be expected to produce accurate answers.

Our work in array processing has been concentrated in two areas this year. First, we have developed a method for using a multiple-beam adaptive array (MBAA) in both slotted and unslotted packet radio networks, and

we have evaluated the performance of single-hop networks using an MBAA. We have shown that an MBAA yields very high throughputs and low delays in such networks. Also, we have found that the performance of an unslotted network with an MBAA can be almost as good as that of a slotted network.

Second, we have begun some new work in angle estimation. The purpose of this work is to generalize existing angle estimation techniques to make it possible to handle signal arrival angles in two spatial coordinates and to incorporate known signal modulations and unknown signal polarizations in the estimator. Some preliminary results have been obtained.

Technology transition continues to take several forms for our JSEP program. First, of course, are the students graduating in this program who carry the knowledge gleaned in their research programs to other users. Second, there are the published papers, both oral and written, which generally attract the attention of other DoD sponsoring agencies. Such agencies in turn provide additional funding and in general make use of our JSEP research and extend it to better their own programs.

Yet another method takes the form of computer codes developed under non-JSEP sources that make extensive use of JSEP research. As we have noted previously, the results of all of these studies are of great importance in the analysis and control of the radiation and scattering from complex shapes.

This continues to be a major task at The Ohio State University ElectroScience Laboratory (OSU-ESL) which is funded by a variety of DoD agencies. A major objective of the ESL funded by other sources is to provide a general computer code (or codes) for the evaluation of the RCS of Aerospace vehicles, but a variety of theoretical analysis must be generated before this goal can become a reality. The OSU-ESL continues to provide

to DoD users a variety of complex computer codes at the cost of materials for radiation from antennas on aircraft, reflector antennas and integral equation formulations based on previous research activities to 94 industrial organizations with DoD approval for use in DoD activities. In fact, last year 154 additional copies of these very complex user friendly codes were issued. This represents about a 30% increase over previous years in spite of cutbacks of DoD funding.

III. DIFFRACTION STUDIES

Researchers:

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1. Introduction

The topics investigated during the past year consisted of the electromagnetic (EM) diffraction by a corner in a plane metallic angular sector, the EM diffraction by discontinuities in planar, dielectric/magnetic material boundaries, the high frequency EM field representations in terms of beams, or rays, for electrically large, closed guiding structures, and the representation of EM caustic fields in a form suitable for analyzing the reflection and diffraction of fields generated by smooth caustics near the points of reflection and diffraction. A substantial progress has been made on these topics as described below.

2. EM Diffraction by a Corner in a Plane Angular Sector

A uniform geometrical theory of diffraction (UTD) solution has been obtained for describing the diffraction by a corner in a planar perfectly-conducting surface. This UTD corner diffraction solution constitutes an important contribution to the UTD area in that a UTD solution for the diffraction by such a fundamental geometry has not been developed previ-

ously, except for one which was conjectured heuristically [1] and which is not as versatile and accurate as the present solution. This solution is uniform in the sense that it keeps the total high frequency field continuous across the corner induced edge diffracted ray shadow boundary cones where the edge diffracted fields become discontinuous. Continuity of the fields is established here in the same manner as that done by the UTD edge diffracted field which makes the total wedge diffracted field continuous across the edge induced geometrical optics incident and reflected ray shadow boundaries. The discontinuities in the geometrical optics incident and reflected fields at the incident and reflected ray shadow boundaries, that are formed by the presence of edges of the plane angular sector, are compensated by the fields diffracted by these edges; whereas, the discontinuities in the edge diffracted fields past the corner are compensated by the corner diffracted field. The special function, or the transition function, which allows the edge diffracted fields to compensate for the discontinuities in the geometrical optics field involves the Fresnel integral as is well known in the UTD for edges. A different transition function is necessary which allows a proper compensation of the discontinuities of the edge diffracted fields past the corner; this transition function has been found in the present work. Furthermore, the properties of this uniform corner diffraction transition function have been studied carefully, both for small arguments (i.e. near the corner induced edge diffraction shadow boundaries) and large arguments (i.e. far from the corner induced edge diffraction shadow boundaries). Most importantly, a very efficient method and an algorithm based on it have been developed to evaluate the UTD corner transition function; this step is crucial in the use of this UTD corner diffraction solution to solve practical diffraction problems. While this UTD corner solution is based on the best available

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estimate for the asymptotic approximation for the current induced on the plane angular sector, it provides results that are in very good agreement with other rigorous numerical approaches for treating the EM scattering by finite plates with corners. The present solution is valid for aspects not close to grazing where the launching and diffraction of edge waves produced by the corner become important; this is due to the fact that the present asymptotic approximation for the current on the plane angular sector is unable to model the effects of edge waves resulting from the presence of the corner. The inclusion of the latter effect is a topic of future research; some initial attempts at predicting these effects have also been made recently at our laboratory.

3. Diffraction by Discontinuities in Planar Material Boundaries

As reported in the 1989 annual report, the study of high frequency scattering by non-conducting and penetrable surfaces can be somewhat simplified by developing equivalent boundary conditions for characterizing such surfaces. These boundary conditions are referred to as Generalized Impedance (for opaque bodies) and Resistive (for transparent) Boundary Conditions (GIBC and GRBC). Once these boundary conditions are developed, it is no longer necessary to calculate the fields inside the material and they are also very suitable in the analysis of scattering problems by means of various functional analytical techniques. One disadvantage is the fact that the solutions developed with these boundary conditions are in general not unique. A lot of effort has been directed to develop additional conditions such as edge and junction conditions which are more general than the usual edge condition. In particular, a junction condition has been developed at the planar junction of two thin dielectric half-planes. Note that the application

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of this junction condition yields a unique solution.

A more general type of coating can be built with chiral material. This type of material has been known to exist at optical frequencies, however, it appears that it can be built at microwave frequencies. A chiral material can be described by three parameters, namely, its permittivity, permeability and an additional parameter, referred to as the chiral admittance. Thus, there is one more degree of freedom which can be used to control the scattering properties of a chiral body. To study the EM diffraction by bodies constructed with chiral material, GIBC/GRBC's have been developed for planar chiral slabs, which can be grounded by a perfect electric conductor. As in the case of dielectric materials, these equivalent boundary conditions will facilitate the analysis of diffraction problems.

It is customary to compare newly developed diffraction solutions with other independent solutions such as those based on the moment method technique. For these purposes, integral equations have been developed for two- and three-dimensional chiral bodies. These integral equations are more efficient than the ones developed by a straight forward application of the volume equivalent current method.

4. Ray and Beam Representations for Fields Coupled into Large Open Cavities

A Gaussian beam shooting approach was developed for analyzing the EM fields coupled into an electrically large open cavity of relatively arbitrary shape, when the open end is directly illuminated by an external source. The fields coupled into the cavity via the open end are described by beams which are launched from an array of points in the aperture at the open end. This array of launch points corresponds to the phase centers of the subapertures into which the original aperture is subdivided. A sufficiently

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dense set of identical beams is launched radially from each phase center
and with constant interbeam angular spacing. The initial beam launching
amplitudes are determined by matching the beams from each subaperture
to the far field pattern of that subaperture with the cavity walls removed.
Furthermore, once launched, the beams are tracked through the interior
cavity region using an axial tracking approximation. In this approximation,
the beams are tracked like real rays along their axes using the rules of
beam optics. To use this approximation, it is necessary to choose highly
focussed (or wide waisted) beams. However, such beams undergo distortion
upon each reflection at the interior walls. Thus, this real ray axial beam
tracking approximation has been found to work well provided the length
of the waveguide cavity is not much larger than four or five times the
maximum aperture dimension at the open front end. One could overcome
this limitation by tracking beams via complex rays; however, complex ray
tracking appears at this time to be a very cumbersome and time consuming
procedure. A significant advantage of the beam approach for representing
the interior cavity field is that the beams need to be tracked only once into
the interior cavity from the array of points in the aperture at the open end
which is illuminated. The beam paths then remain unchanged with change
of illumination or excitation; only the initial beam amplitudes change with
changes in illumination of the aperture at the open end which excites the
cavity. Furthermore, the beams launched into the cavity automatically and
implicitly include the effects of diffraction at the boundary (edge) of the
aperture.

An alternative to tracking beams via complex rays to overcome the
effects of beam distortion indicated earlier is to launch a dense grid of ordi-
nary ray tubes radially from the subapertures instead of launching beams.

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Once launched, the far thinner ray tubes are then tracked via reflections through the cavity via the rules of ray optics. This procedure is referred to as the generalized ray expansion (GRE) which has been developed and shown to work quite well for several representative cases that have been studied recently. This recently developed GRE method maintains the useful features of the beam expansion in that the ray paths in the GRE need to be tracked only once because they do not change with the illumination, and the GRE also implicitly contains effects of the fields which couple into the cavity via diffraction by the edges of the aperture at the open end. It is also noted, however, that a lot more rays need to be tracked with GRE than one needs to track beams in the beam shooting approach. It is noted that the conventional Geometrical Optics ray shooting schemes require a new set of incident rays entering the cavity to be tracked each time the incident angle changes, and they must be modified to explicitly include the effects of fields coupled into the cavity via diffraction at the open end by tracking within the cavity a whole additional set of rays diffracted by the aperture edges, the GRE on the other hand does not have these deficiencies.

As a part of a future effort on this topic, some other ray and beam launching schemes will be studied which would be more easily and conveniently applicable to an aperture of relatively arbitrary shape at the open end. Additional refinements to the GRE will also be investigated to improve the efficiency of the GRE procedure.

5. Caustic Field Analysis

The object here is to find the field scattered from an object when the illuminating field is characterized by a smooth caustic of rays in which the caustic is very close to the scattering surface. If the caustic is far from the scatterer, then the field away from the caustic transition region may be

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represented as a ray optical field whose scattering can thus be calculated using ordinary ray methods. Previous work on our JSEP yielded an asymptotic high frequency solution for the field near a smooth caustic which is uniformly valid across the caustic and which reduces to the correct real and complex ray optical solution in the lit and dark regions, respectively, outside the caustic transition region. However, it is not possible to directly use that uniform expresssion to perform an asymptotic high frequency calculation of the subsequent reflection or diffraction of this caustic field, because it is not in the form of some type of superposition of simpler ray optical fields. What is therefore needed is to express the field near a caustic as a superposition of simple ray optical constituents which can then be tracked upon reflection and diffraction via ray optics. With the above objective in view, a plane wave (spectral) representation has been obtained for the caustic field generated by a concave reflector. It is next desired to reflect or diffract this field by a second scattering object to ascertain the field reflected or diffracted by the latter when illuminated by this caustic field. This part of the study is now in progress. It is noted that a complication can arise because the fields reflected or diffracted from the second scatterer could also exhibit a smooth caustic; this situation will also be incorporated in the study.

References

[1] F.A. Sitka, W.D. Burnside, T.T. Chu and L. Peters, Jr., "First-Order Equivalent Current and Corner-Diffraction Scattering from Flat-Plate Structures," *IEEE Trans. on Antennas and Propagation*, Vol. AP-31, No. 4, pp. 584–589, July 1983.

6. List of Papers - JSEP Diffraction Studies

Published:

1. H.T. Kim and N. Wang, "UTD Solution for the Electromagnetic Scattering by a Circular Cylinder with Thin Lossy Coatings," *IEEE Transactions on Antennas and Propagation*, Vol. 37, No. 11, November 1989, pp. 1463-1472.

2. R.G. Rojas, L.M. Chou, "Diffraction by a Partially Coated PEC Half-Plane," *J. Radio Science*, Vol. 25, March-April 1990, pp. 175-188.

3. J. Choi, N. Wang, L. Peters, Jr. and P. Levy, "Near Axial Back Scattering from Finite Cones," *IEEE Transactions on Antennas and Propagation*, Vol. 38, No. 8, August 1990, pp. 1264-1272.

4. P.H. Pathak and M.C. Liang, "On a Uniform Asymptotic Solution Valid Across Smooth Caustics of Rays Reflected by Smoothly Indented Boundaries," *IEEE Trans. on Antennas and Propagation*, Vol. AP-38, No. 8, August 1990, pp. 1192-1203.

5. J. Choi, N. Wang, L. Peters, Jr. and P. Levy, "Near Axial Backscattering from a Cone Sphere," *Radio Science*, Vol. 25, No. 4, July-August 1990, pp. 427-434.

Accepted for Publication:

1. P.H. Pathak and R.J. Burkholder, "High Frequency EM Scattering by Open-Ended Waveguide Cavities," accepted for publication in *Radio Science*, January-February 1991.

2. G. Pelosi, R. Tiberio and R.G. Rojas, "Electromagnetic Field Excited by a Line Source Placed at the Edge of an Impedance Wedge," accepted for publication in *Journal of Electromagnetic Waves and Applications*.

3. R.J. Burkholder, R-C. Chou and P.H. Pathak, "Two Ray Shooting Methods for Computing the EM Scattering by Large Open-Ended Cavities," accepted for publication in *Computer Physics Communications*.

4. R.G. Rojas, "Integral Equations for the Scattering by Three Dimensional Inhomogeneous Chiral Bodies, accepted for publication in *Journal of Electromagnetic Waves and Applications*.

Submitted for Publication:

1. R.G. Rojas, H.C. Ly and P.H. Pathak, "EM Plane Wave Diffraction by a Planar Two-Part Thin Dielectric/Ferrite Geometry," *J. Radio Science.*

2. R.G. Rojas, H.C. Ly, P.H. Pathak and R. Tiberio "EM Plane Wave Diffraction by a Three-Part Thin, Planar Dielectric/Ferrite Slab," *J. Radio Science.*

3. R.J. Burkholder and P.H. Pathak, "An Analysis of the EM Scattering from an Open-Ended Waveguide Cavity Using Gaussian Beam Shooting."

4. M.C. Liang, P.H. Pathak and C.W. Chuang, "A Generalized Uniform Ray Solution for the Diffraction by a Perfectly-Conducting Wedge with Convex Faces," submitted to *J. Radio Science.*

5. R.G. Rojas, "Integral Equation and Moment Method Solution for Two Dimensional Chiral Bodies," submitted to *IEEE Transactions on Antennas and Propagation.*

Papers in Preparation:

1. R.G. Rojas and L.M. Chou, "Generalized Impedance/Resistive Boundary Conditions for a Planar Chiral Slab".

2. R.G. Rojas, "Integral Equations for the EM Scattering by Two Dimensional Chiral Bodies".

3. R.G. Kouyoumjian, P.H. Pathak and R. Rojas, "The Geometric Theory of Diffraction", for IEEE Proceedings (invited).

4. P.H. Pathak, "High Frequency Methods for Antenna Analysis," for IEEE Proceedings (invited).

5. K.C. Hill and P.H. Pathak, "A UTD for a Corner in a Plane Angular Sector Developed Via PTD Surface Currents."

Conferences/Oral presentations:

1. R.G. Rojas "Integral Equations for the Scattering by Two and Three Dimensional Inhomogeneous Chiral Bodies," presented at the 1990 IEEE AP-S/URSI International Symposium, Dallas, Texas, May 1990.

2. G. Manara, R. Tiberio, G. Pelosi and P.H. Pathak, "Calculations of the Coupling between Two Line Sources in the Presence of an Impedance Wedge," 1990 IEEE AP-S International Symposium and Radio Science Meeting, Dallas, Texas, 1990.

3. R.G. Rojas, H.C. Ly and P.H. Pathak, "High Frequency Diffraction by a Inhomogeneous Thin Dielectric Strip," presented at the XXIII General Assembly of URSI, Prague, Czechoslovakia, August 1990.

4. R.G.Rojas, H.C. Ly, P.H. Pathak and R. Tiberio, "EM Planar Wave Diffraction by a Two- and Three-Part Thin, Planar Dielectric/Ferrite Slab," presented at the 1990 IEEE AP-S/URSI International Symposium, Dallas, Texas, May 1990.

5. R.J. Burkholder and P.H. Pathak, "Application of the Generalized Ray Expansion Method to Analyze the EM Scattering by Arbitrary Open-Ended Waveguide Cavities," 1990 IEEE AP-S International Symposium and Radio Science meeting, Dallas, Texas, 1990.

Invited Lectures (P.H. Pathak):

1. P.H. Pathak and R.J. Burkholder, "On Ray and Beam Expansions for Analyzing EM Coupling into Open-Ended Waveguide Cavities," 1990 IEEE AP-S International Symposium and Radio Science Meeting, Dallas, Texas, 1990, (invited).

2. "On Electromagnetic Scattering by Electrically Large, Open Ended Waveguide Cavities of Relatively Arbitrary Shape," at ONERA, Chalais-Meudon (near Paris), France, August 24, 1990.

3. "Uniform Asymptotic Theories of Edge Diffraction," 23rd General Assembly of the International Union of Radio Science (URSI), Czechoslovak Technical University, Czechoslovak Academy of Sciences, Prague, Czechoslovakia, August 28–September 5, 1990.

4. Presented two invited lectures (one on High Frequency Techniques in Electromagnetic Scattering Analysis, and another on the Analysis of Electromagnetic Scattering from Electrically Large, Open Ended Waveguide Cavities) at a series of seminars on Analytical, Numerical & Experimental prediction of the Radar Cross Section (RCS) of Complex Objects, sponsored by the University of CANTABRIA at Palacio de la Magdelena, Santander, Spain, September 17–20, 1990.

Awards

1. R.G. Rojas received the 1990 Browder J. Thompson Memorial Prize Award, for the best paper in any IEEE publication for an author under the age of thirty, for the paper, "Wiener-Hopf Analysis of the EM Diffraction by an Impedance Discontinuity in a Planar Surface and by an Impedance Half-Plane," IEEE Trans. on Antennas and Propagation, Vol. AP-36, pp. 71-83, January 1988.

IV. INTEGRAL EQUATION ANALYSIS OF EXOTIC MEDIA

Researchers:

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1. Introduction

This section will summarize our work in integral equation studies from July 1, 1989 to the present. In overview, our recent research has centered on integral equation and method of moments (MM) solutions for unusual or novel media. In particular, we are developing MM solutions for scattering by chiral bodies, an MM solution for the chiral microstrip transmission line, and also MM solutions for the analysis of artificial media and nonlinear media.

a. Chiral Media

A chiral media has constitutive relationships of the form

$$\mathbf{D} = \epsilon\mathbf{E} - j\xi\mathbf{B}$$

$$\mathbf{H} = \frac{1}{\mu}\mathbf{B} - j\xi\mathbf{E}$$

where ξ is the chiral admittance. In a regular or achiral media, $\xi = 0$. The non-zero ξ in a chiral media results in an additional coupling between the electric and magnetic fields, and causes the polarization of a plane wave to rotate as it propagates through the chiral media.

One component of our research in chiral media is directed toward the development of an integral equation and MM solution for the scattering

from a chiral cylinder of arbitrary cross section shape. In order to treat inhomogeneous chiral cylinders we employ the volume current formulation in which the chiral cylinder is represented by equivalent electric and magnetic volume polarization currents $(\mathbf{J}, \mathbf{M})$. To this end, we have developed a volume equivalence theorem for chiral media, and have used this theorem to formulate a pair of coupled vector integral equations for the equivalent electric and magnetic currents [1,2]. These coupled vector equations, which are equivalent to six coupled scalar equations, are solved via a pulse basis and point matching MM solution.

In order to verify the accuracy of the MM solution, we developed an (new) exact eigenfunction solution for scattering by a multilayered circular chiral cylinder [3]. For example, Figure 1 shows a comparison of the MM and eigenfunction solution for TE scattering by a circular chiral cylinder. Numerical results generated by the MM solution are in excellent agreement with the exact eigenfunction solution. Note also that the chirality of the media can significantly effect the scattering, with a major effect being a rotation of the polarization of the scattered wave. Recently we have modified the above MM solution to include the presence of a perfectly conducting half plane [4].

Image theory is a simple technique for analyzing bodies over a ground plane. We have extended conventional image theory to include chiral bodies [5]. As illustrated in Figure 2, the image of a chiral body obeys conventional image theory except for a minus sign in the chiral admittance.

As illustrated in Figure 3, our most recent work in chiral media involves a microstrip transmission line on a chiral substrate. This work required the development of the spectral domain Green's function for a grounded chiral slab. This chiral slab Green's function is then incorporated into a

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Chiral Cylinder, Radius = 0.15 meters
$\mu_r = 2$, tan $\delta_m = .05$, Freq. = 300 MHz
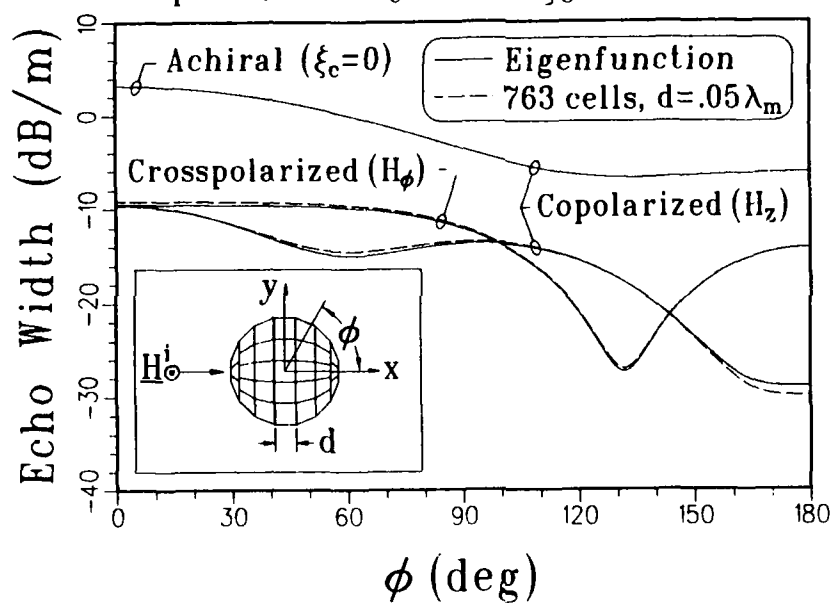$\epsilon_r = 3$, tan $\delta_e = .05$, $\xi_c = .002$

Figure 1: A comparison of the MM and eigenfunction solutions for TE scattering by a chiral cylinder.
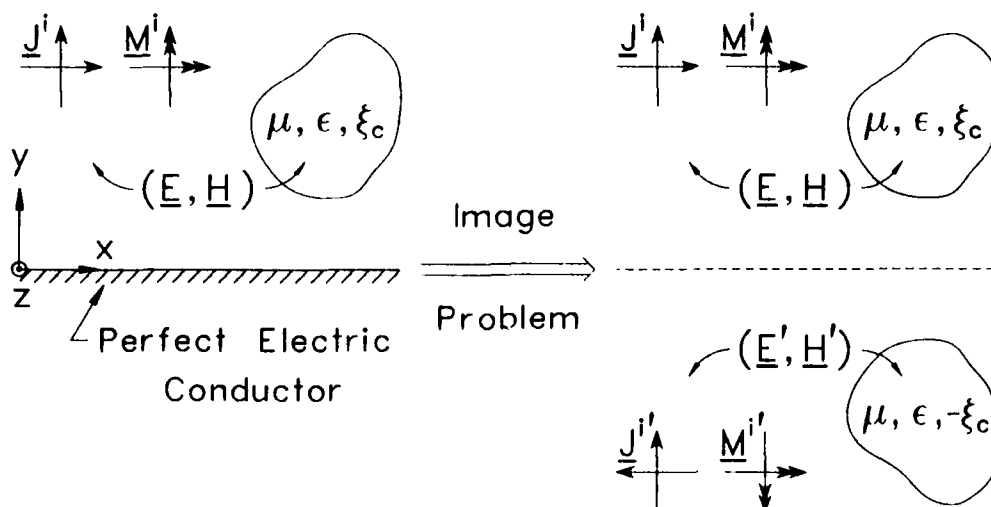
20

CHIRAL IMAGE THEORY

Figure 2: Image theory for a chiral body.
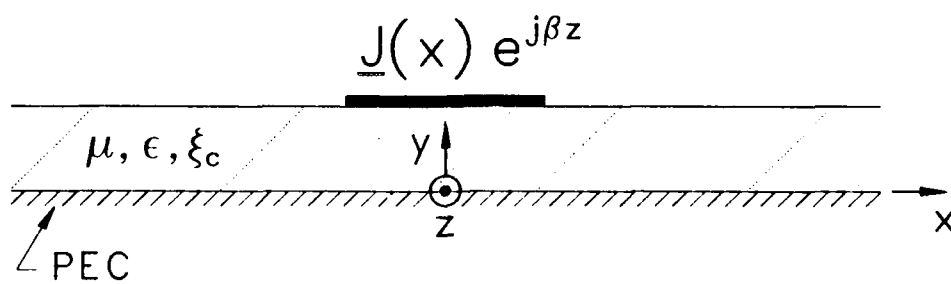
CHIRAL MICROSTRIP

Figure 3: A microstrip transmission line on a chiral substrate.
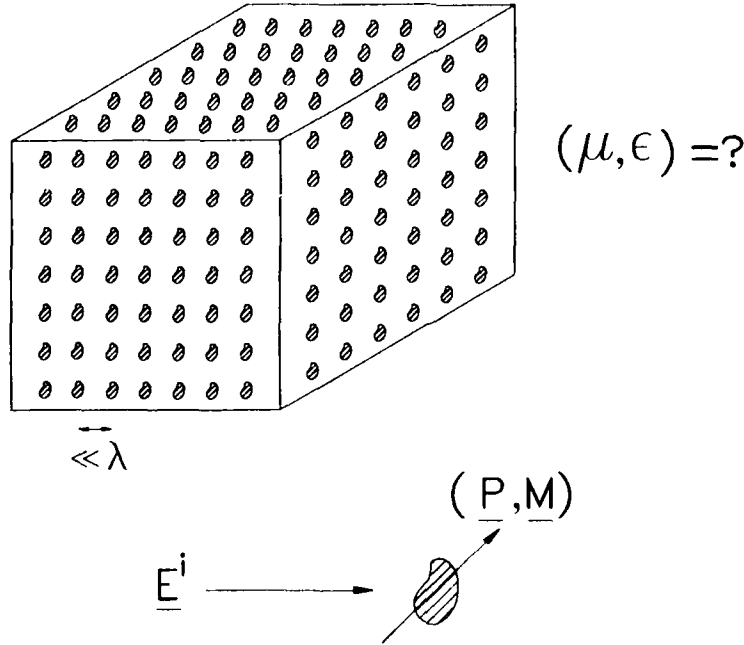
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ARTIFICIAL DIELECTRIC/FERRITE MEDIA

Figure 4: An artificial medium is modeled by a periodic array of small scatterers.

MM solution for the current distribution $\mathbf{J}(x)$ and propagation constant β of a microstrip transmission line on the chiral substrate.

b. Artificial Media

As illustrated in Figure 4, an artificial medium is created by suspending a large number of small scatterers, such as spheres, discs, or dipoles, in some host or background medium. A field propagating in this artificial medium will induce electric and/or magnetic dipole moments in the scatterers. The result is that the artificial medium appears to be a dielectric and/or a ferrite medium. An artificial chiral media can be created from a 3D infinite periodic array of helices.

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Our research is directed toward the use of integral equation and MM techniques for the analysis of artificial media. Essentially, one uses the periodic MM to obtain the impedance matrix for an infinite periodic array of scatterers filling all space. By setting the determinant of this matrix to zero one can determine the normal modes of the system and in turn deduce the equivalent permittivity and permeability of the artificial media. At present we have applied this method to the 2D problem of an infinite periodic array of thin dielectric cylinders, and the 3D problem of an infinite periodic array of short dipoles. The results of this research will be described in a PhD dissertation now in preparation [7].

c. Nonlinear Media

We are interested in the interaction of electromagnetic microwaves with nonlinear devices and nonlinear media. Although such interactions have potentially useful applications, very little effort is currently devoted to this area. In the past 37 years, the nonlinear area has been represented in the IEEE Transactions on Antennas and Propagation only by a few papers on nonlinear plasmas, EMP transmission through a ferromagnetic shield, and scattering by a single dipole with nonlinear load. On the other hand, the areas of nonlinear optics and nonlinear circuits show considerable activity.

A section on nonlinear media was included in The 1989 URSI International Symposium on Electromagnetic Theory. This section consists of four papers from Russia, one paper each from Greece, Italy, Poland, Scotland and Sweden, but none from the U.S.A. Out of these nine papers, three are concerned specifically with nonlinear optics.

We have investigated plane-wave scattering by a periodic planar array of parallel wire dipoles. As illustrated in Figure 5 the single row of dipoles
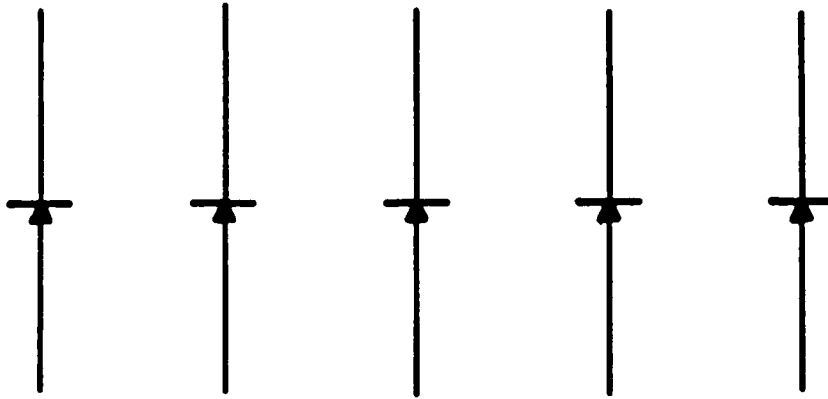
Figure 5: One-row periodic planar array of dipoles with nonlinear loads.

forms a broadside array, and each dipole has a nonlinear load at the center. The load may be series-opposing diodes to represent a nonlinear capacitor, or parallel-opposing diodes to represent a nonlinear resistor. Several time-harmonic plane waves may simultaneously be incident on the array, but each wave has the same direction of propagation and the frequencies are harmonically related. In the steady-state condition the total field is thus periodic in space and time, and Floquet's theorem is applicable.

Even though the incident wave contains only one or several harmonic frequencies, the scattered field will contain an infinite series of harmonics. This series may be truncated, however, and we wish to solve numerically for the complex amplitudes of the various harmonic plane waves scattered (or reflected) in the specular direction. One may also be interested in the amplitudes of some of the grating lobes. It has been observed that new grating lobes may appear when linear loads are replaced with nonlinear loads.

The solution of this problem is simplified by splitting it into two parts.

In Part I the nonlinear loads are removed, and we apply the moment method to solve the scattering problem where a time-harmonic plane wave has oblique incidence on a periodic planar array of dipoles with short-circuited terminals. This procedure is carried out for each harmonic wave incident on the array. For the nth harmonic, one calculates and stores the short-circuit terminal current or the open-circuit received voltage V_n^r induced in the dipoles.

Part I also includes the solution of a phased-array transmitting problem. Again the nonlinear loads are removed, and a one-volt generator is placed at the terminals of each dipole. The moment method is then applied to solve this time-harmonic transmitting problem. This procedure is carried out for each harmonic frequency deemed to be significant in the representation of the total scattered field. For the nth harmonic, one calculates and stores the active antenna impedance Z_n.

Figure 6 illustrates the Thevenin equivalent circuit for a dipole array with nonlinear loads. The open-circuit received voltage $v_r(t)$ and the load voltage $v_l(t)$ are expanded in Fourier series as follows:

$$v_r(t) = Real \sum_n V_n^r \exp(jn\omega_o t) \tag{1}$$

$$v_l(t) = Real \sum_n V_n^l \exp(jn\omega_o t) \tag{2}$$

Of course the active antenna impedance $Z_a(\omega)$ is frequency dependent, and Z_n denotes its value at the nth harmonic frequency. From the basic circuit laws as applied to Figure 6, the load current is given by

$$i(t) = Real \sum_n \frac{V_n^r - V_n^l}{Z_n} \exp(jn\omega_o t) = i_1(t) \tag{3}$$

Now the load current $i(t)$ and the load voltage $V_l(t)$ must be related by the characteristics of the nonlinear load. If each dipole is loaded with
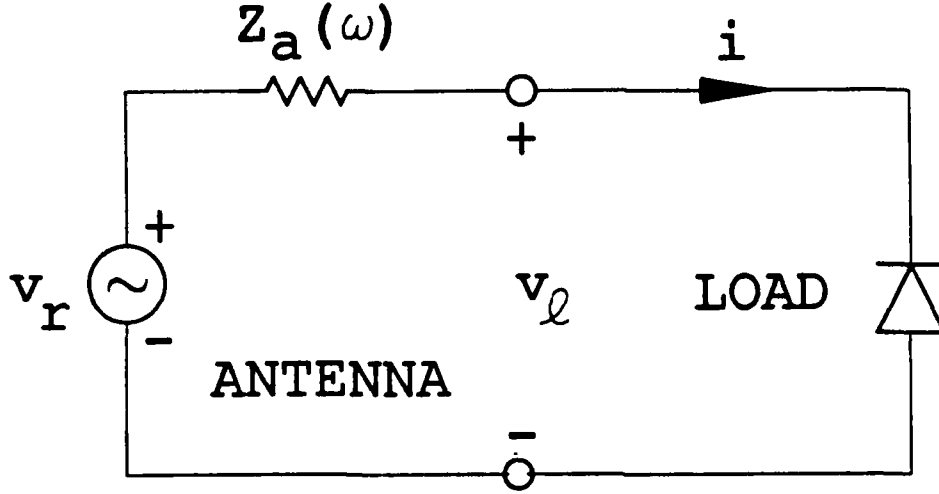
Figure 6: Thevenin equivalent circuit for dipole array with nonlinear loads.

matched parallel-opposing diodes, the current-versus-voltage law may be represented as follows:

$$i(t) = \sum_{n=1} c_n |v_l(t)|^n sgn(t) = i_2(t) \tag{4}$$

where $sgn(t) = 1$ when t is positive, and -1 when t is negative. The analysis may be extended to take account of the load inductance and capacitance, but this detail will not be covered here.

At the outset, one is given the angle of incidence, the frequency, and the complex amplitude of each incident plane wave. The impedances Z_n and the received voltages V_n^r are then calculated as Part I of the analysis. The object of Part II is to determine numerically the load voltage V_n^l. This is accomplished as follows.

From Equations (3) and (4), the currents $i_1(t)$ and $i_2(t)$ must be equal to each other and to $i(t)$. In a least-square solution, one adjusts the voltages V_n^l to minimize the quantity F which is defined as follows:

$$F = \int_0^T [i_1(t) - i_2(t)]^2 \, dt \tag{5}$$

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where $T = 2\pi/\omega_o$ denotes the basic period of the waveform. We have found the gradient search technique to be accurate and efficient for minimizing F. After the load voltages V_n^l and load currents I_n have been determined in this manner, it is a simple matter to calculate the amplitude of the reflected plane wave and the grating lobes scattered by the periodic structure.

Figure 7 illustrates the backscatter echo width for a periodic array of short-circuited dipoles with broadside incidence, as calculated with our new computer program which was developed as part of this study. For comparison Figure 7 also shows the exact backscatter echo width for a perfectly conducting strip with infinite length, and the close agreement between the two results tends to verify the accuracy of the calculated data. In Figure 7 the wire dipoles have perfect conductivity, a radius of 0.005 wavelength and a spacing of 0.05 wavelength, and the width of the strip is equal to the dipole length. Of course, when the spacing is increased, the backscatter characteristics of the dipole array will no longer resemble those of the conducting strip.

For the next example, we selected a nonlinear load consisting of a pair of Schottky diodes (type HSCH-3486) connected in parallel-opposing. Thus, one diode conducts when the load voltage is positive, and the other conducts when the load voltage is negative. Figure 8 illustrates the typical current-versus-voltage characteristics for the HSCH-3486 diode, together with a simple three-term approximation.

Figure 9 illustrates the load current waveforms $i_1(t)$ and $i_2(t)$ defined in Equations (3) and (4). The close agreement between the two calculated waveforms tends to verify the accuracy of the solution. In this example two harmonic plane waves have broadside incidence simultaneously on the one-row periodic array of dipoles. One incident wave has 0.3 volts per meter and
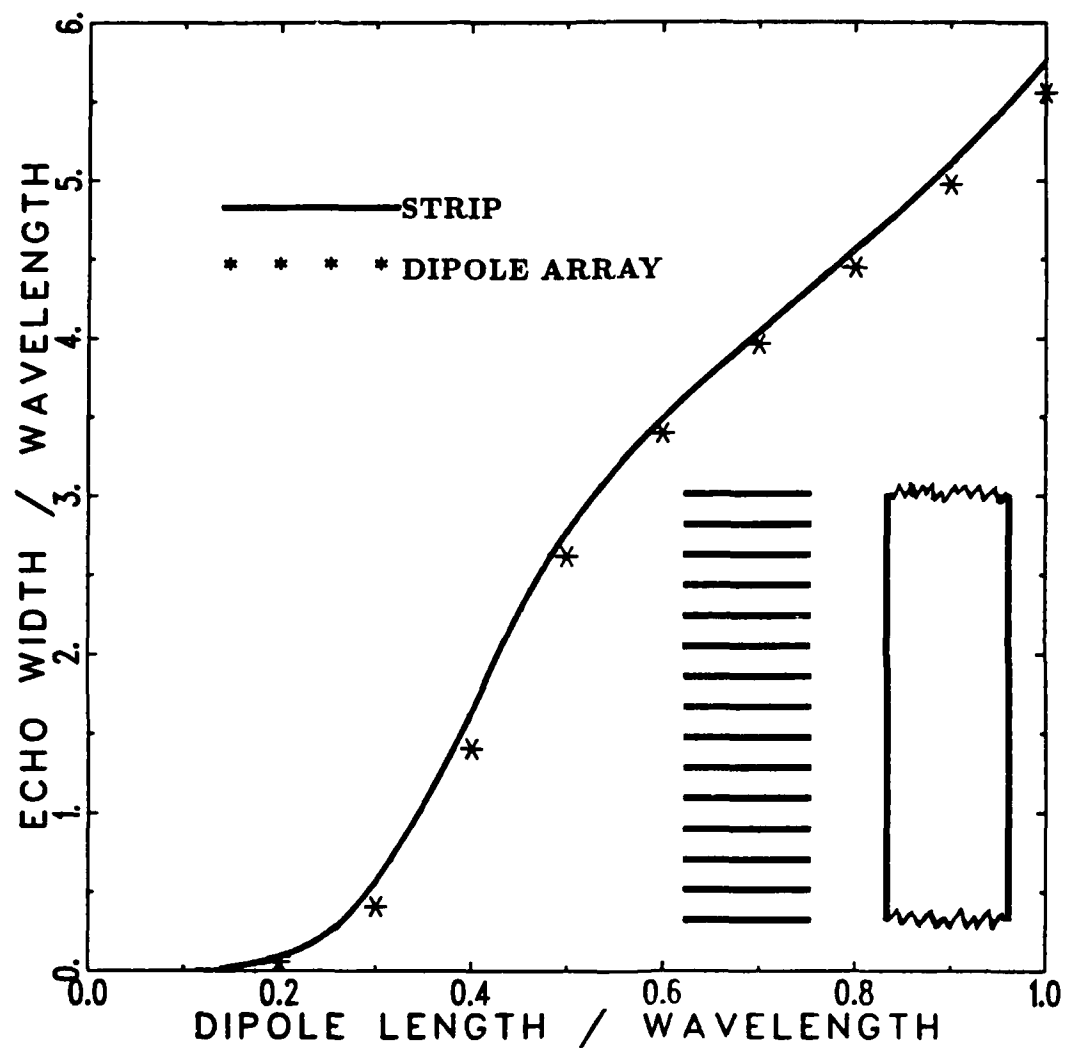
27

Figure 7: Broadside backscatter versus length for dipole array and infinite strip.
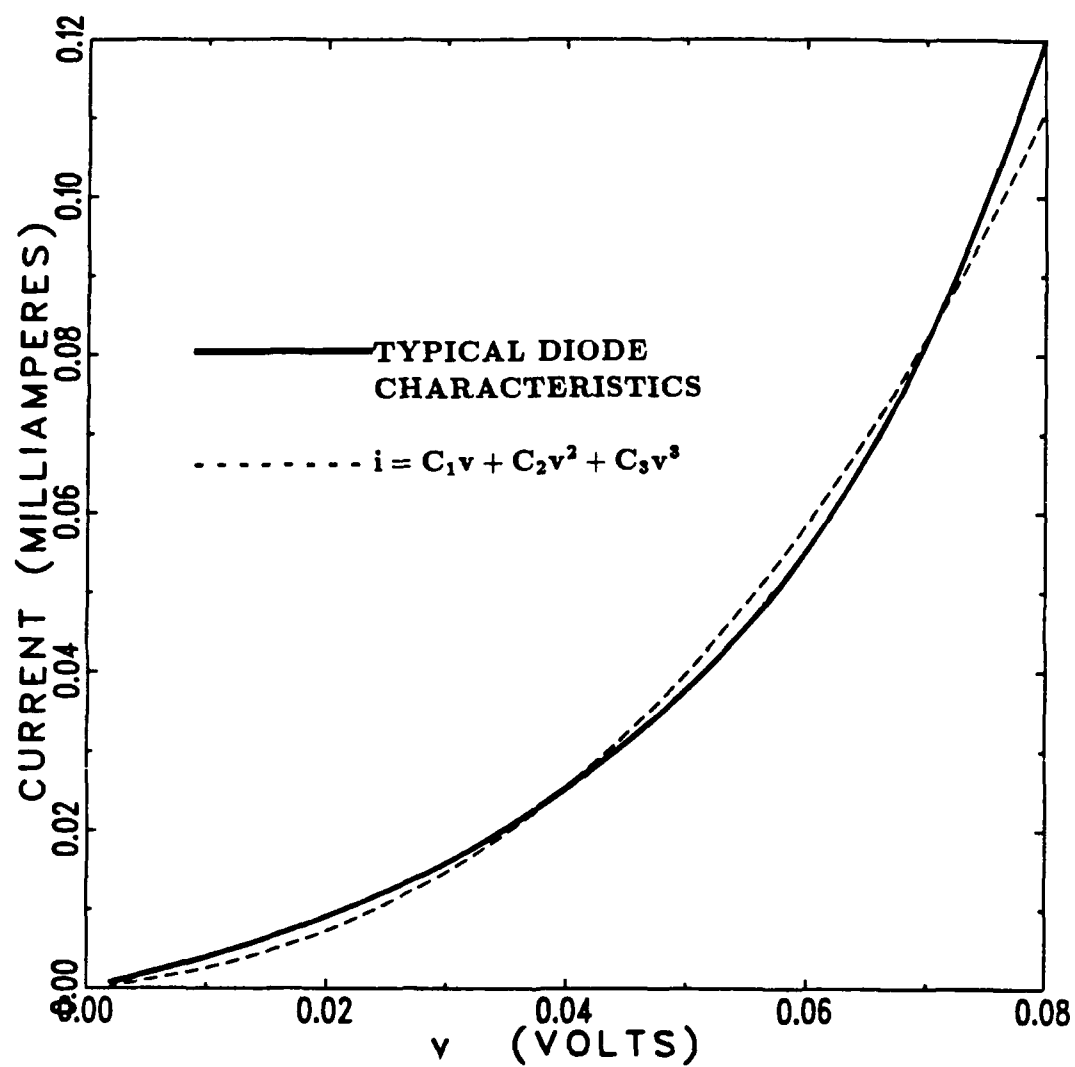
Figure 8: Current versus voltage for Schottky diode HSCH-3486.

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a frequency of 600 MHz, while the other has 0.15 v/m at 900 MHz. At the fundamental frequency (300 MHz), the wire radius is 0.0002λ, the dipole length is 0.25λ, and the dipole spacing is 0.04λ. The free-space wavelength is denoted by λ, and the dipoles are constructed of brass with a conductivity of 10.4 MS/m. Ten harmonic frequencies (300 MHz to 3 GHz) were retained in calculating the load current and the load voltage. The scattered field includes a significant 300 MHz component, which may be considered a subharmonic since this frequency is not present in the incident wave.

To obtain accurate results, the sinusoidal-Galerkin moment method was employed together with the magnetic-frill model of the terminal region of each loaded dipole. At the highest frequency, the length of each dipole is 2.5λ and the moment method involves 23 equations with 23 unknowns.

In this example the gradient-search techniques optimized twenty parameters, namely the real and imaginary parts of ten harmonic load voltages. In this way it minimized the error between the current waveforms $i_1(t)$ and $i_2(t)$.

In the next period, data will be compiled to illustrate some of the interesting results obtainable with this configuration, and a paper will be submitted for publication. In addition, an attempt will be made to investigate the solutions which may propagate on the one-row periodic array of dipoles.

2.   Other Research

The results of some of our past work were published during this reporting period. This work includes:

1. an eigenfunction solution for scattering by a material coated parabolic cylinder [6],
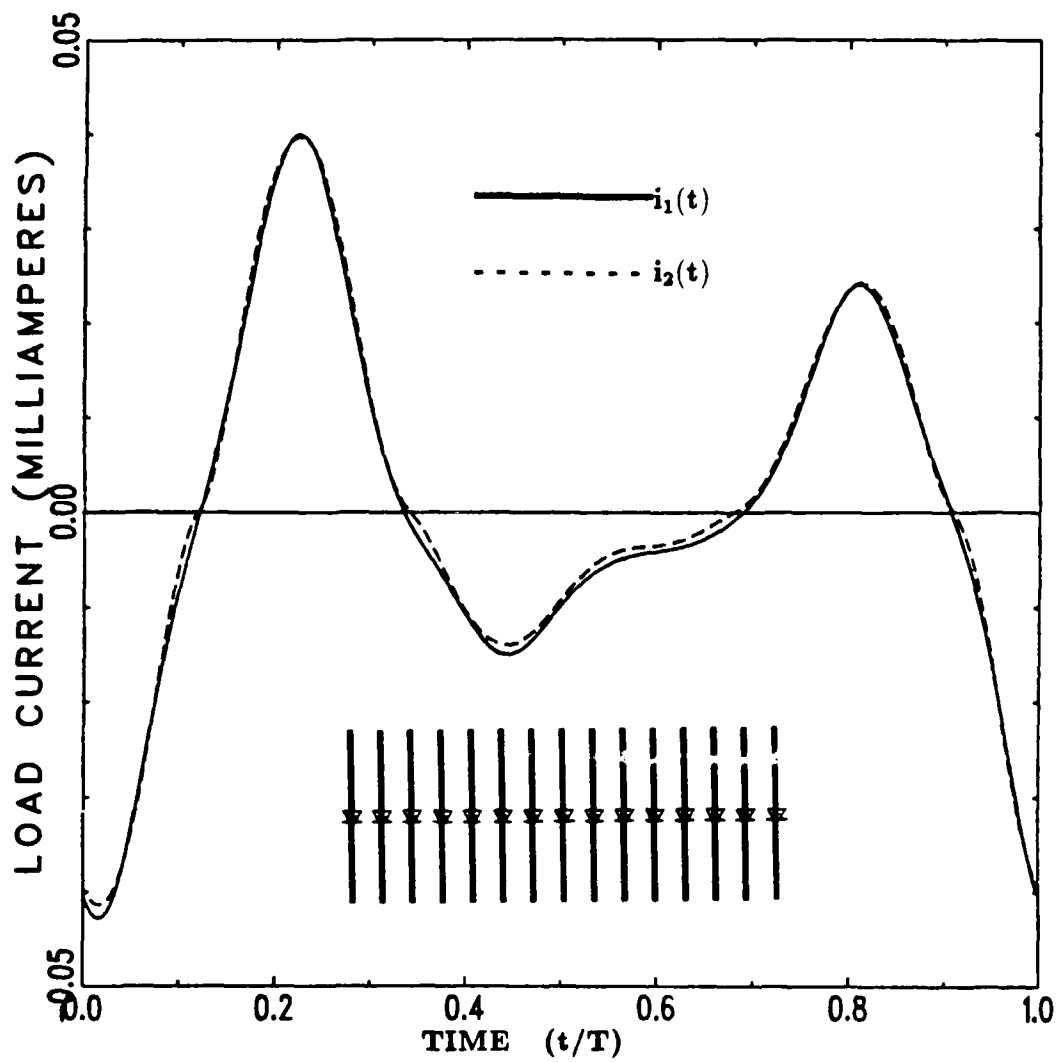
Figure 9: Load current waveform through nonlinear load with two frequencies incident on periodic planar array.

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2. an invited review article on MM modeling of complex bodies [8],

3. an invited tutorial review article on the MM has been prepared [9].

References

[1] M. Kluskens and E.H. Newman, "Scattering by an Arbitrary Cross Section Chiral Cylinder," June 1989 IEEE Antennas and Propagation/URSI Symposium, San Jose, CA.

[2] M.S. Kluskens and E.H. Newman, "Scattering by a Chiral Cylinder of Arbitrary Cross Section," *IEEE Trans. on Antennas and Prop.*, Vol. AP-Vol. 38, Sept. 1990, pp. 1448-1455.

[3] M.S. Kluskens and E.H. Newman, "Scattering by a Multilayer Chiral Cylinder," *IEEE Trans. on Antennas and Prop.*, accepted for publication.

[4] M.S. Kluskens and E.H. Newman, "Scattering by a Chiral Cylinder of Arbitrary Cross Section in the Presence of a Half-Plane," *J. Electromagnetic Waves and Appl.*, submitted for publication.

[5] M.S. Kluskens and E.H. Newman, "Image Theory for Chiral Bodies," *IEEE Trans. on Antennas and Prop.*, accepted for publication.

[6] E.H. Newman, "Plane Wave Scattering From a Material Coated Parabolic Cylinder," *IEEE Trans. on Antennas and Prop.*, Vol. AP-38, April 1990, pp. 541-550.

[7] J.L. Blanchard, "Integral Equation Analysis of Artificial Media," PhD Dissertation, The Ohio State University, Department of Mathematics, in preparation.

[8] E.H. Newman, "Polygonal Plate Modeling," *Electromagnetics*, Vol. 10, Jan.-June 1990, pp. 65-83, (invited paper).

[9] E.H. Newman and K. Kingsley, "An Introduction to the Method of Moments," *Computer Physics Communications*, submitted for publication (invited paper).

3. List of Papers - JSEP Integral Equation Studies

Published:

1. J.H. Richmond, "Axial Slot Dielectric-Coated Elliptic Cylinder," *IEEE Trans. on Antennas and Propagation*, Vol. 37, October 1989, pp. 1235–1241.

2. E.H. Newman, "Plane Wave Scattering from a Material Coated Parabolic Cylinder," *IEEE Trans. on Antennas and Propagation*, Vol. AP-38, pp. 541–550, April 1990.

3. E.H. Newman, "Polygonal Plate Modeling," *Electromagnetics*, Vol. 10, January–June 1990, pp. 65–83, (invited paper).

4. M.S. Kluskens and E.H. Newman, "Scattering by a Chiral Cylinder of Arbitrary Cross Section," *IEEE Trans. on Antennas and Propagation*, Vol. AP-38, pp. 1448–1455, September 1990.

Accepted for Publication:

1. M.S. Kluskens and E.H. Newman, "Scattering by a Multilayer Chiral Cylinder," *IEEE Trans. on Antennas and Propagation.*

2. M.E. Peters and E.H. Newman, "TM Scattering by a General Sheet Impedance Discontinuity," *IEEE Trans. on Antennas and Propagation.*

3. M.S. Kluskens and E.H. Newman, "Image Theory for Chiral Bodies," *IEEE Trans. on Antennas and Propagation.*

4. J.H. Richmond, "On the Variational Aspects of the Moment Method," *IEEE Trans. on Antennas and Propagation.*

Submitted for Publication:

1. E.H. Newman and K. Kingsley, "An Introduction to the Method of Moments," *Computer Physics Communications.* (invited paper).

2. M.S. Kluskens and E.H. Newman, "Scattering by a Chiral Cylinder of Arbitrary Cross Section in the Presence of a Half-Plane," *J. Electromagnetic Waves and Appl.*

Papers in Preparation:

1. J. Blanchard and E.H. Newman, "Method of Moments Analysis of Artificial Media," to submitted to *IEEE Transactions on Antennas and Propagation.*

Theses and Dissertations:

1. M. Peters, "TM Scattering by a Variable Sheet Impedance in a Multilayered Slab," Master's thesis, The Ohio State University, Department of Electrical Engineering, 1990.

2. J.L. Blanchard, "Integral Equation Analysis of Artificial Media," Ph.D. Dissertation in preparation, The Ohio State University, Department of Mathematics.

V. HYBRID STUDIES

Researchers:

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P. Law, Grad. Research Assoc. (Phone: 614/294-9284)

1. Introduction

During the past year, the topics investigated were in the areas of passive MMIC elements and antennas, in the hybrid formulation of EM scattering from and penetration into electrically large open cavities containing a complex interior obstacle, in the hybrid formulation of EM scattering by shallow antenna cavities, and in the hybrid combination of high and low frequency methods for predicting the EM scattering by complex objects. Considerable progress on these topics has been made as described below.

a. Hybrid Analysis of Microstrip and Related Configurations

In order to develop an efficient hybrid analysis of passive MMIC elements and antennas, it is important to study the guiding/radiation properties of various MMIC transmission line configurations. A hybrid analysis leading to a characterization of the MMIC components and antennas can then be formulated in terms of an integral equation which can be solved via the moment method (MM), such an MM employs a hybrid set of basis functions for describing the unknown currents on the MMIC structures which typically reside on a grounded substrate. In particular, a hybrid basis set

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includes the conventional subsectional type in the discontinuity region of the MMIC elements and the traveling wave guiding/radiating modes on the rest of the appropriate regions (typically corresponding to the transmission line regions). Furthermore, in open region problems, the conventional form of the Green's function in the kernel of the integral equation becomes highly inefficient for numerical computations; therefore, an asymptotic form of the planar Green's function with the asymptotic large parameter being the lateral separation of the source and field points (along the substrate) has been developed, such that it remains valid uniformly even for lateral field and source from separations as small as a third of the free space wavelength. Such an asymptotic Green's function was previously developed on our JSEP for the single layer substrate. More recently, it has been extended to a double layer (superstrate-substrate case) and is currently being extended to a triple layer. The merits of extending the asymptotic analysis to arrive at a Green's function which is valid for N number of layers with $N > 3$ are not clear at this time; this aspect is under study. In addition to open region structures, closed region structures, are also currently under investigation, and the utility as well as the limitations of employing closed region configurations to provide information on open region ones will also be subsequently investigated; this connection between the open and closed regions has not been adequately studied in the past except for the fundamental trapped mode on some open guiding structures. For modes that leak energy from the transmission line structure (e.g. microstrip line, co-planar line, slot line, etc.) the ability to use a closed region structure does not become immediately apparent. All of the above studies serve as building blocks wherefrom efficient analysis and design of a variety of MMIC structures and antennas can be performed.

b. EM Scattering from and Penetration into Electrically Large Open Cavities containing a Complex Interior Obstacle

The EM scattering from large, open cavity structures containing a complex obstacle is of great interest in EM scattered field as well as EMC applications. The cavity shape can be relatively arbitrary. This coupled with the fact that the interior obstacle can be complex makes the study of this scattering configuration a rather difficult task. However, it is found that one can break up the analysis of such a general cavity-obstacle configuration into two distinct physical parts. This is done by conveniently choosing a plane S_T near the obstacle. This plane divides the region inside the cavity into one from the open front end of the cavity to the plane S_T, and into another from S_T to the back end of the cavity which contains the complex obstacle. The two parts are analyzed separately; i.e., as two physically different situations distinct from each other. In the first part, the fields are tracked within the first section of the cavity from the open front end, which is directly illuminated by an external source, to the plane S_T; these fields are then allowed to radiate out of S_T using a Kirchhoff approximation that is accurate for electrically large cavities. In the second part, a unit amplitude plane wave EM scattering characterization of the obstacle is obtained for the second section from $.S_T$ to the back of the cavity; this section contains the obstacle. Such a plane wave scattering characterization, where the response to plane waves coming from a set of different directions, can be developed either by analytical, or by numerical methods (e.g. moment method solution of the integral equation for scattering by the second section, or by some other numerical procedure to achieve the same) if the complex obstacle can be modeled adequately in this numerical approach, or, in principle, by measurements if the obstacle is too complex

to be treated using numerical approaches. The information based on the plane wave scattering characterization of the obstacle part of the cavity is stored and then appropriately weighted by the field radiated from S_T of the first section which is known from the first part. The resultant information is required in a reciprocity integral formulation which then formally connects the appropriate fields associated with the two separate parts in this hybrid procedure to yield the desired external field scattered by the complex interior obstacle in the original configuration. The main advantage of this hybrid approach, which has been recently shown to be successful by considering several representative examples, is that it allows one to separately estimate the effects on the overall scattering due to changes in the cavity shape for a given type of complex interior obstacle, and due to different complex interior obstacles for a given cavity shape, respectively. This work was also supported in part by General Electric of Cincinnati, Ohio. Additional extensions of this procedure are under investigation.

c. **Hybrid Analysis of EM Scattering by Antenna Cavity Configurations**

The EM scattering by antenna cavity shapes is being studied using hybrid methods under JSEP support. Previous work under JSEP included a hybrid combination of asymptotic high frequency and modal techniques for the analysis of the scattering from two-dimensional (2-D) antenna cavity shapes for which the modes can be found analytically as well as a hybrid moment method/asymptotic method analysis for 2-D cavities with dominant mode waveguide fed antennas. Current effort is focussed on hybrid methods for the analysis of three dimensional (3-D) antenna cavity configurations.

This past year, the analysis of the scattering from a 3-D rectangular antenna cavity backed by an array of waveguide fed slots was completed. This analysis can include the effect of dielectric material loading on both the waveguide as well as the cavity. Additionally, the dielectric loading material may be different for the two different regions. This cavity configuration was analyzed in two different ways, using a full moment method as well as using an analytical approach based on the single mode approximation for dominant mode waveguide fed antennas that allow such an approximation. Both methods were found to be in good agreement.

Work is currently underway for the analysis of generally shaped 3-D antenna cavities. Using the method of moments, the mutual coupling and self admittance between waveguide fed antennas without the presence of the cavity walls has been determined. Work is in progress to find the coupling of the antennas to arbitrarily shaped cavity walls by applying high frequency asymptotic methods.

d. Hybrid Analysis of EM Scattering from Complex Structures

A hybrid combination of asymptotic high frequency and moment method techniques is being developed to analyze the EM scattering from electrically large complex structures. Asymptotic methods are used on objects which are electrically large and able to be locally approximated by canonical shapes. However, at lower frequencies, such methods are not accurate. On the other hand, the moment method is better suited for analysis of objects which are electrically small. It is a highly accurate method but very inefficient especially at high frequencies. The hybrid method is designed to be a bridge between these two methods. Essentially it uses asymptotics whenever it can to represent just a few moment method basis functions for

the unknown current on the electrically large parts of the structure, and just a few conventional moment method subsectional basis functions on the electrically small, irregular parts of the geometry. Thus, the advantage of the hybrid method lies in its ability to analyze an object which is electrically large but arbitrary without having to use an extremely large number of conventional subsectional or even entire domain basis functions over the whole radiating object.

The configuration being presently studied is a finite perfectly-conducting plate of relatively arbitrary shape on an electrically large perfectly-conducting convex cylinder. Such a configuration can simulate, for example, a fin on a fuselage of an aircraft or a missile. This geometry is too large to be analyzed efficiently by the moment method; yet, no asymptotic solution exists for it. For this geometry, the conventional subsectional basis functions will be used only to represent the unknown current on the fin which is assumed to be electrically small while the cylinder contribution will be taken into account by a few basis functions based on high frequency asymptotics (or UTD).

To generalize this method even further, we will consider how to treat a fin that is not electrically small. At present, we contemplate using subsectional basis set in the regions where the current is rapidly varying, i.e. corners and edges, and asymptotics elsewhere. This allows many more complex objects to be analyzed by such a hybrid procedure.

2. List of Papers - JSEP Hybrid Studies

Published:

1. S. Barkeshli and P.H. Pathak, "Radial Propagation and Steepest Descent Path Integral Representations of Planar Microstrip Dyadic Green's Function," *Radio Science*, Vol. 25, No. 2, March–April 1990, pp. 161–174.

2. K.D. Trott, P.H. Pathak and F. Molinet, "A UTD Type Analysis of the Plane Wave Scattering by a Fully Illuminated Perfectly-Conducting Cone," *IEEE Trans. on Antennas and Propagation*, Vol. AP-38, No. 8, August 1990, pp. 1150–1160.

3. S. Barkeshli, P.H. Pathak and M. Marin, "An Asymptotic Closed Form Microstrip Surface Green's Function for the Efficient Moment Method Analysis of Mutual Coupling in Microstrip Antennas," *IEEE Trans. on Antennas and Propagation*, Vol. AP-38, No. 9, September 1990, pp. 1374–1383.

4. M. Marin, S. Barkeshli and P.H. Pathak, "On the Location of Proper and Improper Surface Wave Poles for the Grounded Dielectric Slab," *IEEE Trans. on Antennas and Propagation*, Vol. AP-38, No. 4, April 1990, pp. 570–573.

Accepted for Publication:

1. S. Barkeshli and P.H. Pathak, "On the Dyadic Green's Function for a Planar Multi-Layered Dielectric/Magnetic Media," *IEEE Trans. on Microwave Theory and Techniques.*

2. A. Nagamune and P.H. Pathak, "An Efficient Plane Wave Spectral Analysis to Predict the Focal Region Field of Parabolic Reflector Antenna for Small and Wide Angle Scanning," *IEEE Transactions on Antennas and Propagation.*

3. M. Marin and P.H. Pathak, "An Asymptotic Closed-Form Representation for the Grounded Double Layer Surface Green's Function," *IEEE Transactions on Antennas and Propagation.*

Submitted for Publication:

1. P.H. Pathak and R.J. Burkholder, "A Reciprocity Formulation for Calculating the EM Scattering by an Obstacle within an Open-Ended

Waveguide Cavity," submitted to *IEEE Transactions on Microwave Theory and Techniques*.

Papers in Preparation:

1. P.H. Pathak, A. Nagamune and R.G. Kouyoumjian, "An Analysis of Compact Range Measurements,"

2. P.H. Pathak, P. Law and R.J. Burkholder, "High Frequency Electromagnetic Scattering by a Large Obstacle/Termination within an Open Cavity Structure."

Conferences/Oral Presentations:

1. G.A. Somers, P.H. Pathak and I.J. Gupta, "Electromagnetic Scattering by Metallic Tapes on Paneled Compact Range Reflectors," 1990 IEEE AP-S International Symposium and Radio Science meeting, Dallas, Texas, 1990.

2. P.H. Pathak, P.H. Law, G. Crabtree and D. Foreman, "High Frequency Electromagnetic Scattering by Open Ended Waveguide Cavities with a Complex Interior Termination," 1990 IEEE AP-S International Symposium and Radio Science Meeting, Dallas, Texas, 1990.

Invited Lectures (P.H. Pathak):

1. "Analysis of EM Scattering by Electrically Large Open-Ended Waveguide Cavities with an Interior Termination," Texas Instruments, Dallas, Texas, October 11, 1989.

2. "A Hybrid Approach for the Efficient Analysis of Microstrip Configurations," IEEE AP-S lecture, Dallas, Texas, October 11, 1989.

VI. ADAPTIVE ARRAY STUDIES

Researchers:

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James Ward, Graduate Research Associate (now at MIT Lincoln Lab)

1. Introduction

During the past year we have done research under the JSEP contract in two areas related to arrays:

1. High throughput packet radio with adaptive arrays

2. High resolution angle estimation

We discuss these areas below.

2. High Throughput Packet Radio with Adaptive Arrays

We have continued our research on adaptive arrays in packet radio systems from last year. We have obtained exciting results showing that the throughput-delay performance of random access packet radio systems can be substantially improved by using adaptive arrays.

At the end of last year's JSEP contract, we had completed an initial study of the performance of a single-hop slotted ALOHA system using a single-beam adaptive array and were preparing a paper on that work. (That paper was submitted this year [1].) We had also begun work on the use of a multiple-beam adaptive array (MBAA) in a slotted packet radio system. This work has been continued during the past year, and a paper describing

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an MBAA in a slotted system and deriving its performance has also been submitted [2].

In most packet radio protocols studied to date, it is assumed that a given terminal in a packet radio network can receive only one packet at a time. When two packets collide, it is assumed that neither packet is received correctly. In some cases, a *capture* effect [3,4,5,6,7] may exist due to, for example, differences in power levels of the incoming packets. A capture effect allows one packet to be received correctly even if a collision occurs. But even with capture, it is still assumed that a terminal can receive only one packet at a time.

However, this limitation can easily be overcome by using a multiple-beam adaptive array in the packet system. An MBAA is an adaptive antenna system in which several array output signals are formed simultaneously from the same antenna elements. Each output signal is obtained by using a different set of adaptive weights to combine the element signals. In this way, each output signal has a different pattern, with its beam and nulls in different directions.

By using an MBAA in a packet system, it is possible to receive *multiple* packets simultaneously in each slot. The antenna patterns can be adaptively controlled so each beam of the MBAA has a maximum pointed at a different incoming packet and has nulls on colliding packets. This technique yields enormous increases in throughput and reductions in delay.

The performance of a single-beam adaptive array in a packet system is similar to that of Carrier Sense Multiple Access[1] (CSMA) [8]. But when a multiple-beam adaptive array is used, a much more substantial improvement is obtained. One can achieve average throughputs of 2 to 3 packets

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[1] However, an adaptive array has the advantage over CSMA that with an adaptive array it is not necessary that all terminals in the network be able to hear each other.

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per slot, for example, with only modest MBAA capabilities.

The use of an MBAA to achieve high throughput and low delay in a packet system may be viewed as an alternative to spread-spectrum techniques, which have also been considered as a means of receiving more than one packet in the same slot [9,10]. The use of spread spectrum also allows multiple packets to be received, either by separating packets on the basis of arrival times (with *delay* capture, which separates packets with the same code [11]) or by using orthogonal codes on different packets (with Code Division Multiple Access (CDMA) [9,10]). However, spread spectrum techniques have the disadvantage that they require much wider bandwidths than those needed to support the data modulation. An MBAA system requires only the data bandwidth.

Figure 10 shows a typical performance curve for a packet radio receiver with an MBAA. It shows the average conditional throughput $S(j)$ as a function of the number of blocked users j for a network with 50 terminals and an MBAA with $K = 1$ to 6 beams. These curves were computed for a new packet transmission probability $P_n = 0.02$, a blocked packet retransmission probability $P_r = 0.2$, and for an array with 10 elements that can resolve packets 5° apart. It may be seen how the conditional throughput increases significantly when the adaptive array is included and as the number of beams is increased. Conditional throughputs of nearly 4 packets per slot are possible with a 6-beam adaptive array. Adding an MBAA to a packet system also improves the stability of the system.

During this year, we have also begun studying the use of adaptive arrays in unslotted ALOHA systems. An unslotted system is more difficult to analyze than a slotted system. Also, an MBAA in an unslotted system requires quite different techniques for timing acquisition and array adap-
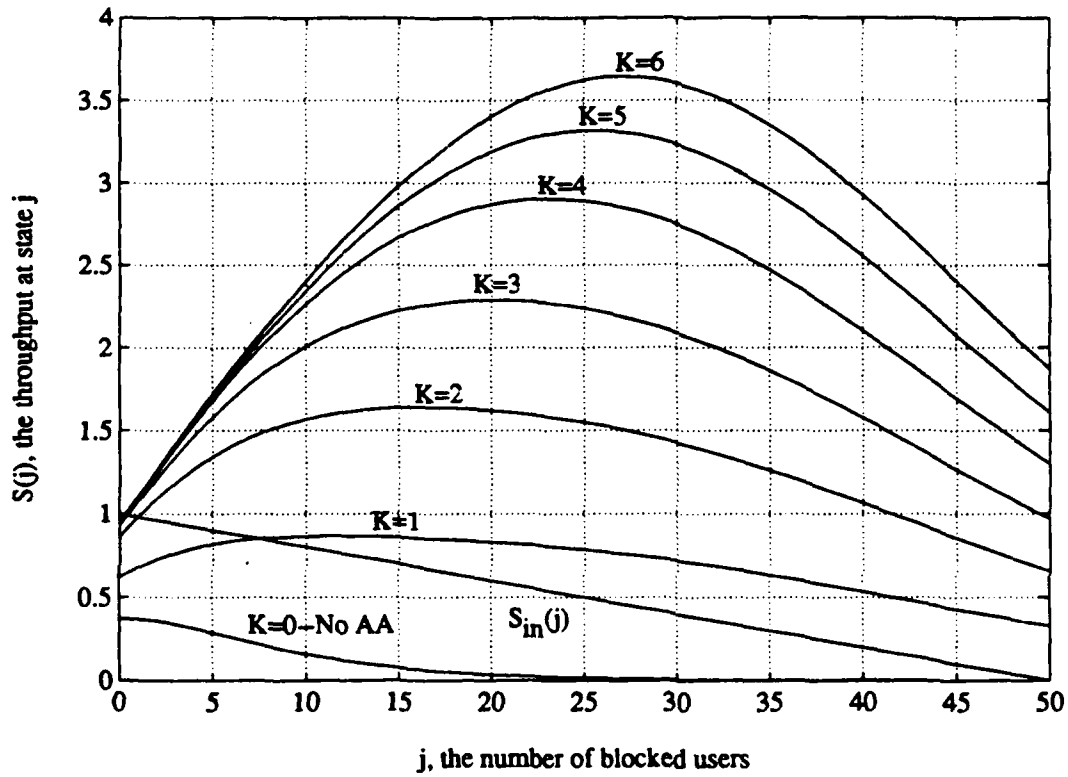
Figure 10: Average conditional throughput $S(j)$ and traffic load $S_{in}(j)$ for a network with 50 terminals and an MBAA with K beams. (New packet transmission probability $P_n = 0.02$, backlogged packet transmission probability $P_r = 0.2$, 8 nulls, 63 bit PN acquisition code.)

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tation than one in a slotted system, because of the asynchronous nature of the unslotted case. Interfering packets may arrive at any time during a received packet, so the array must be able to adapt throughout an acquired packet. (In the slotted case, adaptation is completed during the preamble and the interfering packets are nulled prior to the message portion of the packet.)

We have developed a promising method for using an MBAA in an unslotted system. For this method we have determined the throughput of an unslotted ALOHA receiver using an MBAA as a function of the number of beams, the number of degrees of freedom and the angular resolution of the array. Our analysis is based on a method similar to that of Tobagi [12] as applied to a spread spectrum multiple access network [10]. We have also done simulations to verify the analysis. Our results show that the throughput of an unslotted system can also be significantly improved with an MBAA. Moreover, an MBAA brings the performance of an unslotted system close to that of a slotted system.

Fig. 11 shows the throughput for a network of $M = 20$ terminals when the packet receiver uses an adaptive array with a single beam. Curves are shown for different numbers of nulls N in the array. The $N = 0$ case corresponds to standard unslotted ALOHA (with zero capture). These curves are for the ideal case when the array can resolve signals arbitrarily close in angle. The curve for $N = 19$ corresponds to perfect capture. For all traffic loads G, the throughput increases as N is increased. The improvement in throughput with additional nulls may be seen.

Fig. 12 shows typical curves of the throughput of an unslotted system with $M = 20$ terminals using an MBAA with $N = 8$ nulls. The parameter K in the figure is the number of beams formed by the MBAA. Curves are

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shown for $K = 1, 3, 5, 7$ and 9. In Fig. 12a, the array can resolve packets with arbitrarily small angular separation ($\theta_r = 0°$), but in Fig. 12b the array can resolve packets only above a $\theta_r = 5°$ separation. Fig. 12b shows theoretical results in the solid curves and simulation results in the dashed curves. Note that this system achieves an average throughput above 2.5 packets per packet length, and it does this in an unslotted system!

Finally, Fig. 13 shows a comparison between a slotted and an unslotted system using an array with 8 nulls in a network of 20 terminals.

3. High Resolution Angle Estimation Techniques in Packet Radio

Our work has shown that the performance of packet radio networks can be significantly improved by taking advantage of the directional properties of arrays. This observation has motivated us to consider other ways of using active antenna processing in packet systems.

It appears that an even greater improvement in packet radio throughput and delay could be achieved by using angle estimation techniques in such systems. For example, consider a slotted packet radio system in which an array with several elements is used at a packet receiver. Suppose that instead of receiving packets in real time during each slot, we instead sample the output of each array element during the slot interval and store the samples in computer memory. Then, at the end of each slot, after the signals have been received, we combine the samples from the array elements with several different sets of array weights. Each set of weights will be chosen to receive one packet and null the others. In order to do this, it is necessary to do two things at the end of each slot:

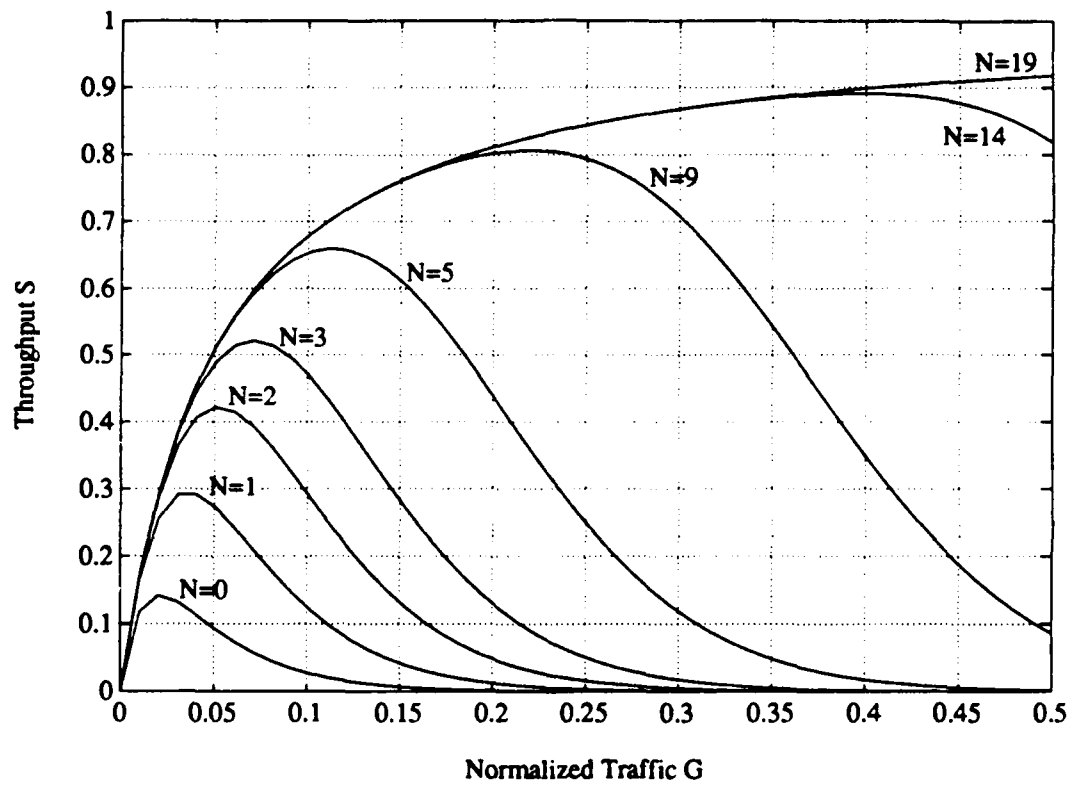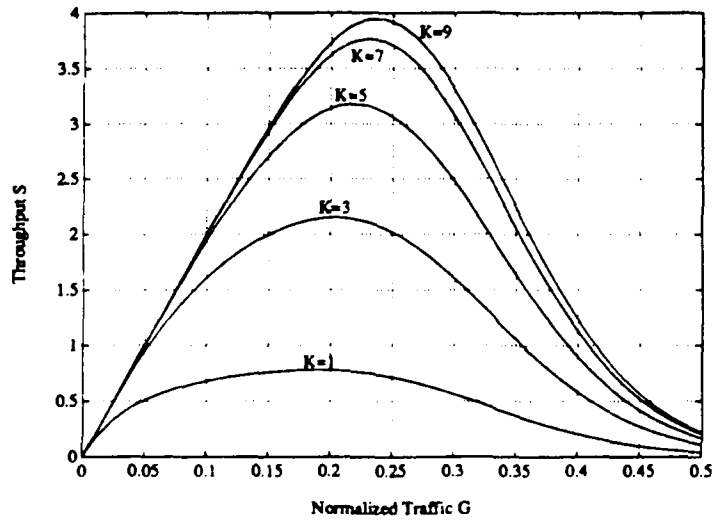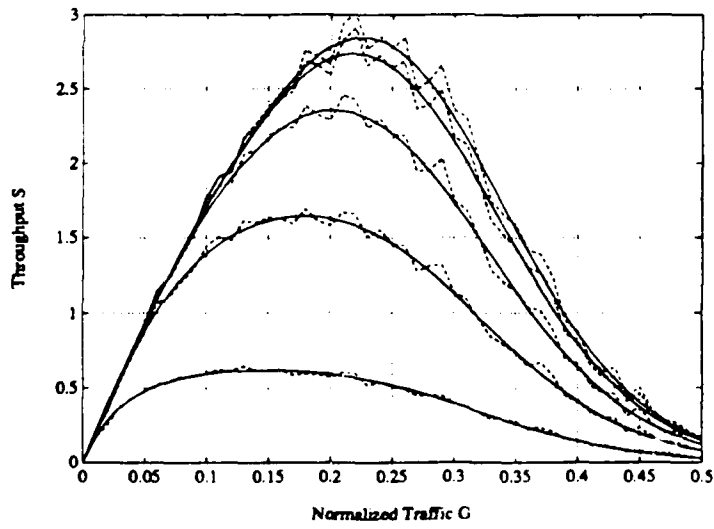1. Estimate the number of packets J that arrived during the slot, and

Figure 11: Throughput for a single-beam adaptive array. $M = 20$, $\theta_r = 0°$

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(a)

(b)

Figure 12: Throughput for an MBAA with $N = 8$ nulls and $M = 20$ terminals. (a) $\theta_r = 0°$. (b) $\theta_r = 5°$. Solid line: theory; Dashed line: simulation)
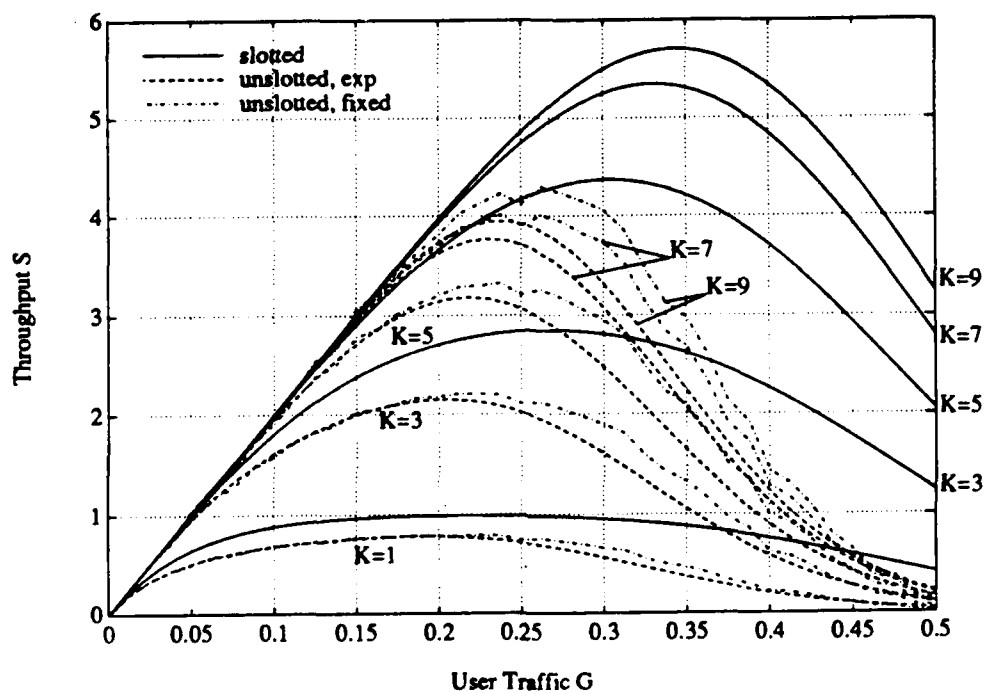
Figure 13: Comparison of unslotted and slotted throughput for a 10-element MBAA as the number of beams is varied. $M = 20$, $N = 8$, $\theta_r = 0°$. (Solid: slotted; dashed: unslotted-exponontial packet lengths; dashdot: unslotted-fixed packet lengths)

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2. Estimate the arrival angles θ_j, $1 \leq j \leq J$, for each of the J packets in the slot.

When J and the θ_j have been estimated, we then calculate J sets of array weights. Each set of array weights will be chosen to form a pattern with its maximum toward one of the incident packets and nulls on all the others. These array weights can then be applied to the signal samples stored in RAM to create J different array output signals, each containing only one incident packet. In this way, all the incident packets in each slot can be received without distortion. The cost required to achieve this advantage is the fixed delay involved in storing the samples and weighting them after the end of the slot. However, this fixed delay is small compared to the retransmission delay encountered in a busy network that is trying to receive packets in real time. The ultimate performance of such a "delay-and-weight" system depends on the number of array elements, the packet signal-to-noise ratios, the angular separation between packets, and so forth.

During the past year of the JSEP contract, we have begun to study this approach. We started by considering the ang   estimation techniques that would be used to implement such a system. To date, we have submitted two papers for publication based on this work.

The first paper [13] considers Maximum Likelihood (ML) estimation of packet arrival angles for the case where each packet contains a known PN (pseudonoise) code at the beginning of the packet. Such an acquisition code was used for our MBAA technique and we were interested in whether including such an acquisition code improves the performance of an ML estimator.

In a second paper [14], we have considered the use of the ESPRIT algorithm [15] and shown how it may be used in a cross-polarized arrays to

estimate both the arrival angles and the polarizations of signals.

We plan to continue work in this area under the follow-on JSEP contract.

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4. List of Papers - JSEP Adaptive Array Studies

Accepted for Publication:

1. C.A. Olen and R.T. Compton, Jr., "A Numerical Pattern Synthesis Algorithm for Arrays," *IEEE Transactions on Antennas and Propagation.*

2. J. Ward and R.T. Compton, Jr., "Sidelobe Level Performance of Adaptive Sidelobe Canceller Arrays with Element Reuse," *IEEE Transactions on Antennas and Propagation.*

Submitted for Publication:

1. J. Ward and R.T. Compton, Jr., "Improving the Performance of a Slotted ALOHA Packet Radio Network with an Adaptive Array," *IEEE Transactions on Communications.*

2. J. Ward and R.T. Compton, Jr., "High Throughput Slotted ALOHA Packet Radio Networks with Adaptive Arrays," *IEEE Transactions on Communications.*

3. J. Li and R.T. Compton, Jr., "Maximum Likelihood Estimation of the Arrival Direction of a Signal with Known Waveform," *IEEE Transactions on Acoustics, Speech and Signal Processing.*

4. J. Li and R.T. Compton, Jr., "Angle and Polarization Estimation using a Signal Subspace Approach with a Polarization Sensitive Array," *IEEE Transactions on Antennas and Propagation.*

Papers in Preparation:

1. J. Ward and R.T. Compton, Jr., "High Throughput Unslotted ALOHA with Adaptive Arrays."

2. J. Li and R.T. Compton, Jr., "Two-Dimensional Angle and Polarization Estimation Using the ESPRIT Algorithm."

3. J. Li and R.T. Compton, Jr., "Angle and Polarization Estimation in a Coherent Signal Environment."

4. J. Li and R.T. Compton, Jr., "Maximum Likelihood Angle Estimation for a Signal with Known Waveform in the Presence of Interfering Signals."

Conferences/Oral Presentations:

1. J. Ward and R.T. Compton, Jr., "Sidelobe Level Degradation in Adaptive Sidelobe Cancellers with Element Reuse," 1990 IEEE International Antennas and Propagation Society Symposium, May 7-11, 1990, Dallas, TX.

2. F.W. Vook and R.T. Compton, Jr., "The Bandwidth Performance of Linear Adaptive Arrays with Tapped Delay-Line Processing," 1990 IEEE International Antennas and Propagation Society Symposium, May 7-11, 1990, Dallas TX.

3. C.A. Olen and R.T. Compton, Jr., "A Numerical Pattern Synthesis Algorithm for Arrays," 1990 IEEE International Antennas and Propagation Society Symposium, May 7-11, 1990, Dallas TX.

Dissertation:

1. J. Ward, "High Throughput Packet Radio Networks with Adaptive Antenna Arrays," August, 1990.